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Technical Notes

Comparative Surface Heat Transfer Measurements in Hypervelocity Flow

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I. Introduction

RELIABLE prediction of the high heat transfer rates experienced during the hypersonic portion of planetary entry and descent is critical to vehicle survival. Two types of sensors that can be used to measure surface heat flux are coaxial thermocouple gages and thin film resistance thermometers. Individually, both types of gages have been used successfully in a number of studies [1–19]. Both thermocouple and thin film gages measure surface temperature from which heat transfer can be calculated. Both have μs response times, and can be flush-mounted in models. Coaxial thermocouples are robust, can survive challenging experimental conditions, and are typically used in higher enthalpy flows. Thin film resistance gages typically provide improved signal levels, but are less robust, have to be individually calibrated, and are typically used in lower enthalpy flows. As a result, there are few studies which directly compare measurements from the two types of gages. In the present work, we perform experimental measurements at a range of intermediate enthalpies in hypervelocity flow and make direct comparisons between temperature histories and heat flux data obtained from thermocouple and thin film gages.

Miller [8] performed a comprehensive review of thin film gages used in the NASA Langley Continuous Flow Hypersonic Tunnel, comparing their performance to thick-skin calorimeters. Gage durability was tested, and it was found that of the four glass substrate models, only one survived longer than one test. The ceramic models fared slightly better, with one surviving six tests, and the other surviving all nine tests. Since these experiments were conducted in a continuous-flow facility the gages were exposed to test times 3 orders of magnitude longer than typical impulse facility test times. The method used to apply the gages to the substrate was different than the current technique which could have significant effects of gage durability.

Kidd presents a detailed survey of the coaxial thermocouples used at Arnold Air Force Base [9]. Some issues associated with the coaxial gages are quantified, and the study concluded that coaxial thermocouples can be used at test times much longer than semi-infinite body assumption would allow, and also that the gage length does not need to be equal to the model wall thickness. Coaxial thermocouple gages, based on a new design by Sanderson [14], are typically used in the Caltech T5 reflected shock tunnel facility [15,16,20]. Marineau and Hornung found that the response time and accuracy of the gages was strongly dependent on the junction geometry [21]. Salvador et al. report on the development of coaxial thermocouple gages for use in the shock tunnel facilities at the Laboratory for Aerothermodynamics and Hypersonics [22]. One important result from this paper is that gage response time depends on the connection properties between the two electrodes, and simply using different grit sandpaper to create the junction changed the response time by a factor of two.

While not focused on direct comparative measurements, there are a limited number of studies in which both thin film and thermocouple surface heat transfer data are available. Both thin film and thermocouple gages were used in two recent studies at Calspan–University of Buffalo Research Center (CUBRC). The first study focused on real gas effects in both the LENS I shock tunnel and LENS X expansion tube facilities for test gas enthalpies from 2 to 12 MJ/kg [2]. Heating rates measured by both gages were in good agreement with each other, however, at high enthalpies the measured heat flux did not agree with either fully-catalytic or noncatalytic wall predictions. The second study at CUBRC, conducted in the LENS I reflected shock tunnel, used the gages to investigate the role of catalytic effects on a sphere-cone model in both nitrogen and carbon dioxide. Tests were run at test gas enthalpies of 2, 6, and 8 MJ/kg. This study found good agreement between the gages, but found that all gage types measured heating levels higher than predicted assuming a noncatalytic wall, but less than that predicted assuming a fully-catalytic wall [3]. A recent study at the CUBRC facility found good agreement between both gages at enthalpies 5 and 10 MJ/kg [23].

Though these sensors have been used extensively for many years, their selection has relied on very general distinctions, where thin film gages are used for "low" enthalpy conditions, and coaxial thermocouples are used for "high" enthalpy conditions. To develop a more rigorous methodology, properties such as signal-to-noise ratio, durability, accuracy, and wall catalysis effects must be quantified for a range of flow enthalpies.

II. Experimental Setup

The hypervelocity expansion tube (HET) at the University of Illinois operates across a range of Mach numbers from 3.0 to 7.5 and stagnation enthalpies from 4 to 8 MJ/kg [24]. For this study, three test conditions with different stagnation enthalpies were selected, Table 1.

The thermocouples used in these experiments are based on the design of Sanderson [14]. They are coaxial, 2.4 mm in diameter, type E (Constantan–Chromel), and mount flush with the surface of a model. The two coaxial elements are connected by an extremely thin junction ($\sim$1 μm) at the surface. The robust design of the gages make them highly resistant to particulate damage [14]. The output signal is processed by a differential amplifier circuit mounted exterior to the test section. Individual calibration of thermocouples is not necessary, since the temperature response of all common thermocouple types is well known. The National Institute of Standards and Technology (NIST) thermocouple reference tables were used to convert from voltage to temperature [25].

The thin film gages used in this study are based on the design of Adelgren [26], Chadwick [6], and Kinnear and Lu [27]. Gages are created by painting and firing a small strip of metallo-organic platinum paint on to an insulating substrate, such as ceramic or glass, to create thin film resistors, whose resistance changes with temperature. The gage is used as one arm in a basic Wheatstone

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Table 1 Theoretical parameters for HET test conditions

Condition	Air 4	Air 5	Air 6
Mach number	5.12	7.45	5.73
Static temperature, K	676	642	909
Static pressure, kPa	8.1	0.8	1.9
Velocity, m/s	2664	3779	3457
Density, kg/m^3	0.042	0.004	0.007
Test time, μs	361	163	242
Unit Reynolds number, 1/m	3.42E6	0.50E6	0.63E6
Stagnation enthalpy, MJ/kg	4.08	7.65	6.70

bridge circuit. A differential amplifier is then used to find the difference between the two bridge legs.

Each thin film gage must be individually calibrated in situ in order to determine the resistance-temperature relationship. A thermal bath was used to calibrate the model-mounted gages for a range of temperatures between 25 and 50° C (chosen based on the expected temperature rises in the HET) and a calibration curve was fit to these data. The calibration curve was found to be linear for all gages used.

To compare both gage types, it was necessary to expose them to a known heat flux while operating in the HET facility. Two model geometries were selected: a sphere and a flat plate. Two reduced expressions to calculate four at the stagnation point of a sphere were derived by Sutton and Graves [28], Eq. (1), and Filippis and Serpico [29], Eq. (2). These expressions are extensions of the theory of Fay and Riddell to different gases and higher enthalpies, respectively:

$$\dot{q} = K\sqrt{\frac{p_s}{R}}(h_{0,e} - h_w) \tag{1}$$

where p_s is the stagnation pressure, R is the sphere radius, $h_{0,e}$ is the test gas stagnation enthalpy, h_w is the wall enthalpy, and K is a constant based on the gas composition:

$$\dot{q} = 90\sqrt{\frac{p_s}{R}}(h_{0,e} - h_w)^{1.17} \tag{2}$$

The equation derived by Filippis is valid for air, while the Sutton and Graves equation can be applied to any gas mixture. Theoretical predictions for laminar flat plate heat transfer were calculated with the reference enthalpy method of Simeonides [30].

III. Error Analysis

To make comparative measurements between the two gages it was necessary to evaluate the error for each gage type. Davis [15] identified two main sources of uncertainty for the thermocouple gages. Firstly, there is error in the voltage-to-temperature conversion due to uncertainty in the NIST temperature conversion tables. Davis reports this to be 1.7% in the temperature change, which corresponds directly to a 1.7% error in the heat flux. Secondly, uncertainty in the thermal properties of the thermocouple materials was determined by Davis to be 8%.

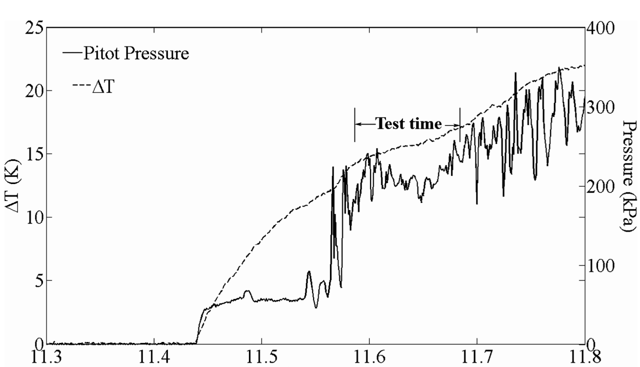

Fig. 1 Temperature rise and pitot pressure history in Air 4.

Table 2 Comparison of experimental thermocouple heat transfer with theoretical predictions (in MW/m^2)

Condition	Experimental	Sutton and Graves [28]	Filippis and Serpico [29]
Air 4	7.85 ± 0.63	6.29	6.40
Air 5	7.74 ± 0.62	5.41	6.15
Air 6	8.50 ± 0.68	5.66	6.28

For both gage types the physical sources of uncertainty are the same, but the magnitudes are different. To determine the thin film gage error in the voltage-to-temperature conversion the goodness of the calibration fit was evaluated. A full scale error approach was used over a 50° range, following Davis [15]. The average difference between the measured calibration point and the calibration curve was used as the error in the temperature measurement. The error from the voltage-to-temperature conversion was found to range between 0.1% and 6.7% with an average of 2.96%. The error in the thermal property was taken from Miller [8]. Though his method is different than that used here, Miller cites an unpublished Calspan report which uses the same gage construction method used here, and found an uncertainty of 5% in the thermal properties. These uncertainties were independently determined by CUBRC and the values used here are in good agreement with those determined by CUBRC [23].

IV. Results

A. Stagnation Point Results

To obtain directly comparable experimental results for both gages, two spherical models were designed. A thermocouple was mounted at the stagnation point of a 25.4 mm diameter stainless steel sphere. For the thin film gages, a hemispherical blunt-body model with 25.4 mm nose diameter was created from MACOR, and a gage was painted at the stagnation point.

A representative comparison between the thermocouple temperature rise and the pitot pressure trace is shown in Fig. 1. The response time compares very well with the pitot pressure history. The experimentally measured heat fluxes for each test condition, and the theoretical predictions are listed in Table 2. It is evident that in every case the heat transfer is underpredicted by theory. This is consistent with the results obtained by Marineau and Hornung [31]. The equation developed by Filippis provides the best prediction of the heat flux, with a 23% deviation in Air 4, a 26% deviation in Air 5, and a 35% deviation in Air 6. Though catalysis effects have been shown in the past to augment heat flux measurements in similar facilities, previous work in the HET has shown that catalytic effects are not expected to be an issue at these conditions [32].

No thin film gages survived at the stagnation point. When measured between successive shots, changes in resistance were typically on the order of 500%. This is most likely due to damage from the high temperatures, shear forces, and particulates. A second problem arose due to the exposed connection between the silver leads and the wire connection which led to a significant increase in the signal-to-noise ratio.

B. Flat Plate Results

A flat plate at a zero degree angle of incidence was chosen as the second model geometry due to both its simplicity and the existence of theoretical predictions of heat flux. Also, the flat plate solved both issues discussed in the previous section that were experienced with the stagnation point thin film gage. With the flat plate design the connection between the silver leads and the feedthrough wire were shielded from the flow, and the parallel mounting direction of the gages decreased the chances of damage. It was also necessary to take into account the establishment time for steady boundary layer flow. Gupta [33] carried out a series of numerical calculations to determine

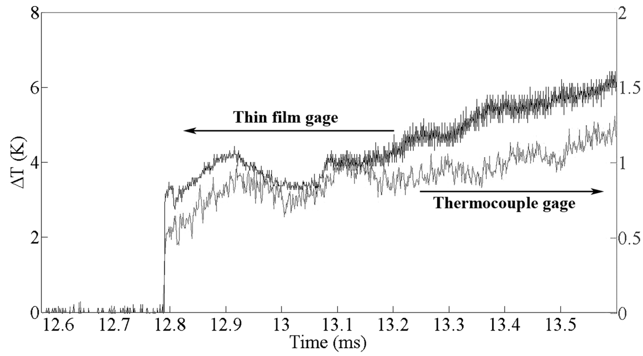

Fig. 2 Comparison of thermocouple and thin film temperature traces in Air 4.

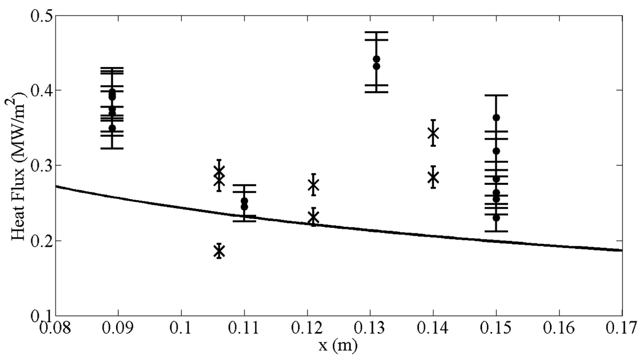

Fig. 3 Comparison of thin film (×), thermocouple (●) heat flux data, and theory (-) vs downstream direction in Air 4 (leading edge at $x = 0$).

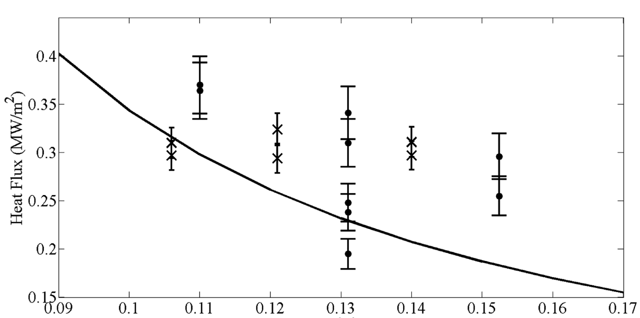

Fig. 4 Comparison of thin film (×), thermocouple (●) heat flux data, and theory (-) vs downstream direction in Air 6 (leading edge at $x = 0$).

the time required for the test gas boundary layer to relax to steadiness on a flat plate in an expansion tube, t_s:

$$t_s = \frac{L}{0.3u_e} \tag{3}$$

where L is the distance along the plate, and u_e is the test gas velocity. Figure 2 shows a thermocouple temperature trace compared with a thin film gage temperature trace. Figures 3 and 4 show the comparison of the thin film data with the thermocouple data for the three test conditions. All three conditions show good agreement between gages near the leading edge, and measurements are in reasonable agreement with theoretical predictions from Simeonides [30], Table 3. It should be noted that both the thermocouples and thin film gages generally show an increase over the theory with increasing x-location on the plate. This is currently under investigation.

V. Conclusions

Thermocouples and thin film gages are used extensively for surface heat transfer measurements in hypersonic impulse facilities. Coaxial thermocouples are robust, can survive challenging experimental conditions, and are typically used in higher enthalpy flows. Thin film resistance gages provide improved signal levels, but have to be individually calibrated, are less robust, and are typically used in lower enthalpy flows. The goal of this work is to make directly comparative measurements in flow fields accessible to both gage types with stagnation enthalpies between 4.08 and 7.52 MJ/kg.

Both gages have been successfully used in the HET on spherical and flat plate models, and the heat transfer data are consistent. Tests demonstrate that thermocouple gages are preferable for use in stagnation regions due to the extremely poor survivability of thin film gages. Both gages show reasonable agreement in the flat plate case, though thin film gages have less noise, a higher signal level, and more consistent response time. Thus, in mounting locations where survivability is not an issue, thin film gages are the preferred gage type.

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Table 3 Comparison of experimental and theoretical flat plate data with percent differences from theory

x, mm	Air 4 experimental, MW/m²						Air 6 experimental, MW/m²				
					Thermocouple gages						
89	0.40	0.39	0.39	0.38	0.37	0.35	—	—	—	—	—
89	54%	53%	52%	45%	43%	36%	—	—	—	—	—
111	0.25	0.25	—	—	—	—	0.37	0.36	—	—	—
111	9%	6%	—	—	—	—	24%	22%	—	—	—
131	0.44	0.43	—	—	—	—	0.34	0.31	0.25	0.24	0.20
131	107%	102%	—	—	—	—	47%	34%	7%	3%	16%
152	0.36	0.32	0.28	0.26	0.26	0.23	0.30	0.26	—	—	—
152	83%	61%	42%	33%	28%	16%	58%	36%	—	—	—
					Thin film gages						
106	0.29	0.28	0.19	—	—	—	0.31	0.30	—	—	—
106	24%	19%	21%	—	—	—	5%	9%	—	—	—
121	0.27	0.23	—	—	—	—	0.29	0.32	—	—	—
121	24%	5%	—	—	—	—	13%	24%	—	—	—
140	0.34	0.28	—	—	—	—	0.31	0.30	—	—	—
140	67%	38%	—	—	—	—	50%	43%	—	—	—

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